JOHNS HOPKINS MEDICINE

Advanced Ultrasound Imaging in Interventional Medicine

Emad M. Boctor, Ph.D.
Assistant Professor of Radiology, Division of Medical Imaging Physics,
The Russell H. Morgan Department of Radiology
and Radiological Science.
eboctor@jhmi.edu

AAPM 2010

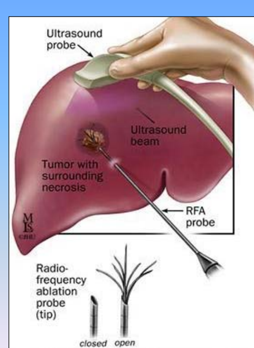
MUSiiC Research Laboratory | Laboratory for Computational Sensing + Robotics | ERC | CISST | JOHNS HOPKINS UNIVERSITY

Disclaimer

- Overview and understanding, not comparison
- Not every possible work will be discussed (lack of time)
- Not every group or individual will be covered (lack of time)
- There is no financial interest with the companies mentioned in this presentation

Driving Application: Liver Ablation

- Hepatocellular Carcinoma (HCC): 1M cases per year (worldwide)
- The most frequent hepatic malignancy in USA is metastatic disease from colorectal cancer
- Resection -- 5 year survival rates between 25% and 55%
- Most patients do not qualify for resection
- un-resectable liver tumors are ablated under ultrasound guidance



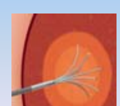
Radiofrequency ablation of a liver tumor

Thermal Ablation of Liver Tumors

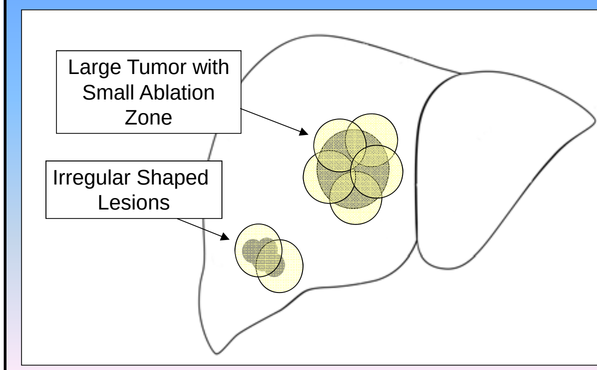
Problems with the Free-Hand Approach

- Dependent on physician accuracy
- Often requires multiple passes
- Unsuccessful ablation rate = 5%
- Inconsistent
- Not repeatable
- Post-ablation evaluation


Targeting


Monitoring

Situations in Which 3DUS Guidance May Be Most Useful



Proposed Solutions

Passive / Passive
- Freehand 3D Ultrasound
- Passive arm for needle

Passive / Active
- Freehand 3D Ultrasound
- Robot Needle Placement

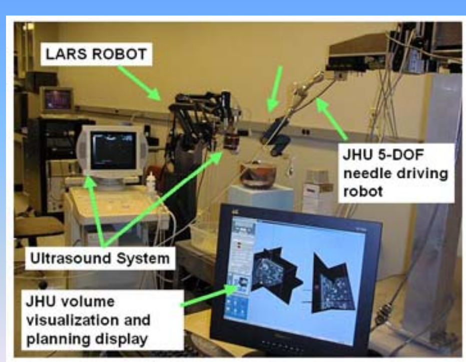
Active / Passive
- Robotic 3D Ultrasound
- Passive arm for needle

Active / Active
- Robotic 3D Ultrasound
- Robot Needle Placement

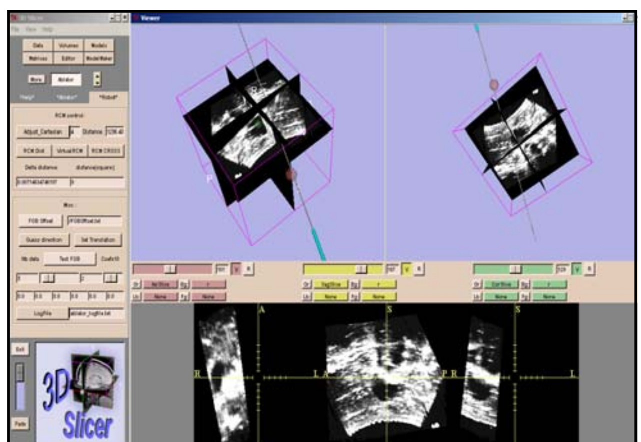
No Robot → 1 Robot → 2 Robots

- Boctor E.M., Fichtinger G., Taylor R.H., and Choti M.A. "Tracked 3D ultrasound in radio-frequency liver ablation", SPIE 2003, Vol. 5035, p. 174-182, 2003.
- Boctor E.M., Taylor R.H., Fichtinger G., and Choti M.A. "Robotically assisted intraoperative ultrasound with application to ablative therapy of liver cancer", SPIE 2003, Vol. 5029, p. 281-291, 2003.

A Dual-Armed Robotic System

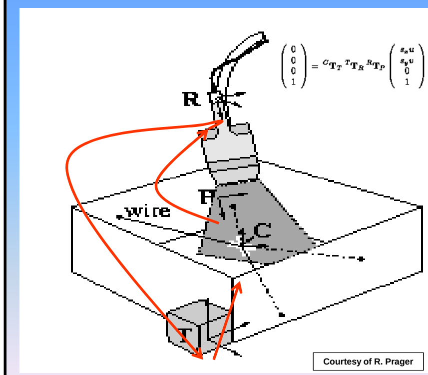


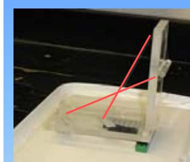
- Boctor E.M., Fischer G., Choti M.A., Fichtinger G., and Taylor R.H. "Dual-Armed Robotic System for Intraoperative Ultrasound Guided Hepatic Ablative Therapy: A Prospective Study", IEEE 2004 International Conference on Robotics and Automation, in proceedings, pp. 377-382.

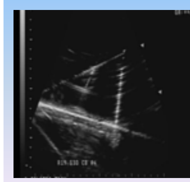


- Boctor E.M., Viswanathan A., Pieper S., Choti M.A., Taylor R.H., Kikinis R., and Fichtinger G. "CISUS: An integrated 3D ultrasound system for IGT with modular tracking interface",SPIE 2004, Volume 5367, pp. 247-256.

Ultrasound Calibration

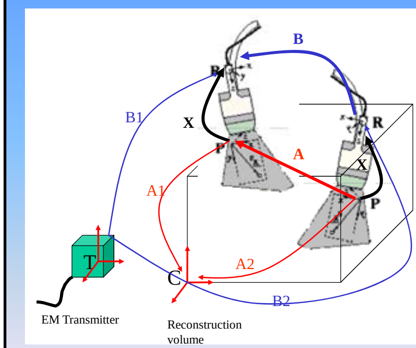






- Prager et al. "Rapid calibration for 3-D freehand ultrasound" UMB 1998.
- Galloway et al, UMB 2001, Abolmaesumi et al, MICCAI 2006, Khamene et al, MICCAI 2005, …

Closed form formulation



$$B = B_2^{-1} B_1$$

$$A = A_2 A_1^{-1}$$

$$AX = XB$$

- Boctor E.M., Viswanathan A., Choti M.A., Taylor R.H., Fichtinger G., and Hager G.D. "A Novel Closed Form Solution For Ultrasound Calibration", ISBI 2004, in proceedings, pp 527-530.
- Daniilidis et al., IJRR 1999.

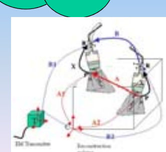
How to solve AX=XB ?

$$R_a R_x = R_x R_b$$
$$R_a t_x + \lambda t_a = R_x t_b + t_x$$

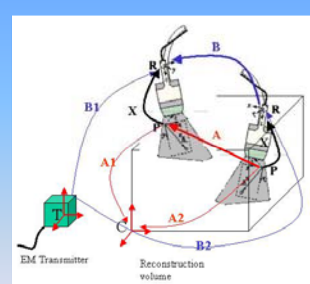
$$(R_a \otimes R_b) vec(R_x) = vec(R_x)$$
$$(I_3 \otimes t_b^t) vec(R_x) + (I_3 - R_a) t_x - \lambda t_a = 0$$

$$\begin{bmatrix} I_9 - R_a \otimes R_b & 0_{9*3} & 0_{9*1} \\ I_3 \otimes t_b^t & I_3 - R_a & -t_a \end{bmatrix} \begin{pmatrix} vec(R_x) \\ t_x \\ \lambda \end{pmatrix} = \begin{pmatrix} 0_{9*1} \\ 0_{3*1} \end{pmatrix}$$

$$UV + VW = T$$
$$(U \otimes I + I \otimes W) vec(V) = vec(T)$$
$$vec(CDE) = (C \otimes E^T) vec(D)$$



Patient Specific in vivo Calibration

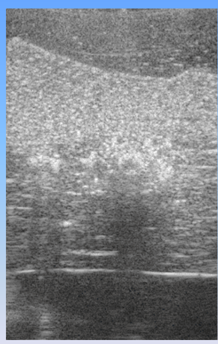


If only we could estimate "*A* " without phantom…

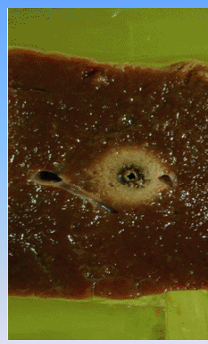
$$AX = XB$$

- Boctor et al., MICCAI 2005, and SPIE 2006.
- Wein and Khamene SPIE 2008.
- Barratt et al., MICCAI 2005.

Ablation under US Guidance is Blind

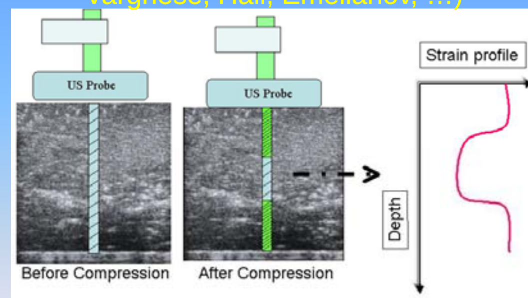


B-mode image



Gross-pathology

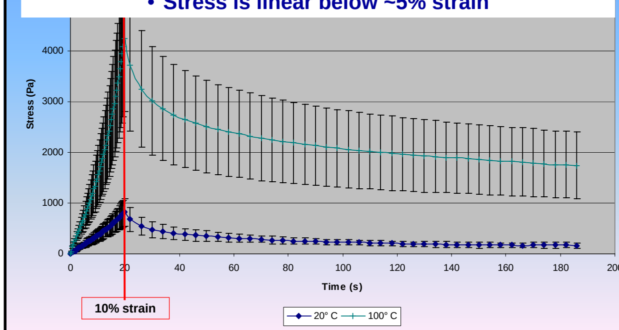
Elastography
(Pioneered by Ophir, Sarvazyan, Bamber, Varghese, Hall, Emelianov, …)



2D representation of strain based imaging model. Before compression: the overlay represents 1D cascaded particles with uniform spacing. After compression: the overlay represents two groups of particle spacing. Small spacing (light green) indicating soft tissues moved more (high strain) than the hard tissue (low strain).

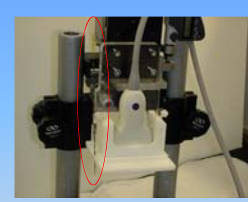
Stress-Strain Measurements

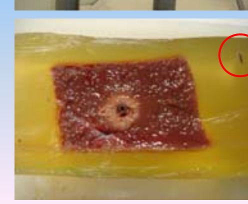
- **Elasticity changes are immediate and permanent**
- **Cooked and raw liver can always be told apart**
- **Young's modulus ratio is ~10**
- **Stress is linear below ~5% strain**



Ex vivo Imaging Study

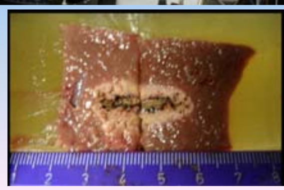
- Supporting gelatin
- Fiducials markers in transparent gelatin
- Radionics single-rod ablator device
- Ellipsoidal ablation along the needle shaft
- Large ablation in short time by using cool-tip technology



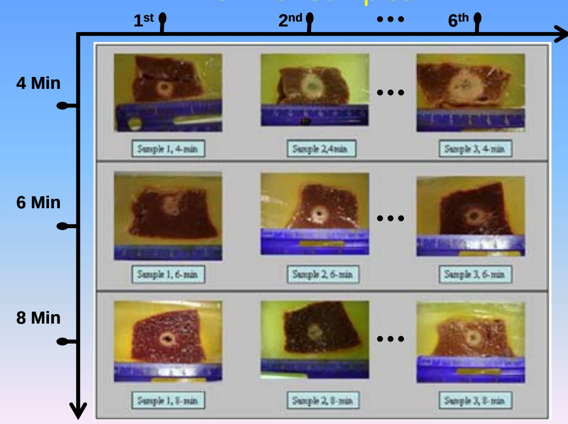


Registration between Elasticity Image and Gross-pathology

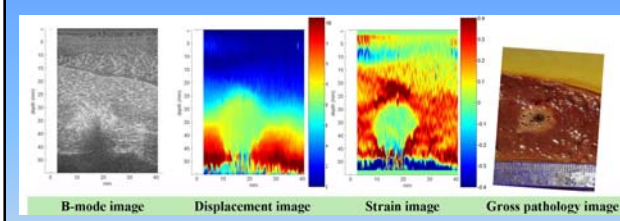
- Supporting gelatin
- Fiducials markers in transparent gelatin
- Radionics single-rod ablator device
- Ellipsoidal ablation along the needle shaft
- Large ablation in short time by using cool-tip technology



The Liver Samples

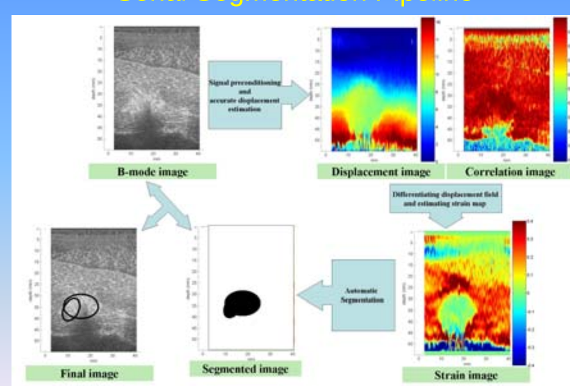


Strain Results

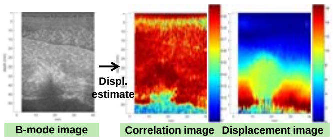


B-mode image shows ex-vivo liver boundaries embedded in gel based medium. It is not possible to differentiate the ablated area from B-mode. Strain is generated from differentiating a displacement map in the axial direction. Strain provides clear evidence of the presence of hard lesion, which is in agreement with the gross pathology picture.

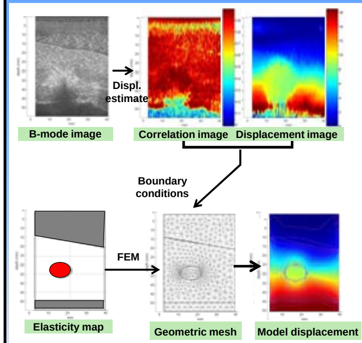
Serial Segmentation Pipeline



Elasticity-based Segmentation



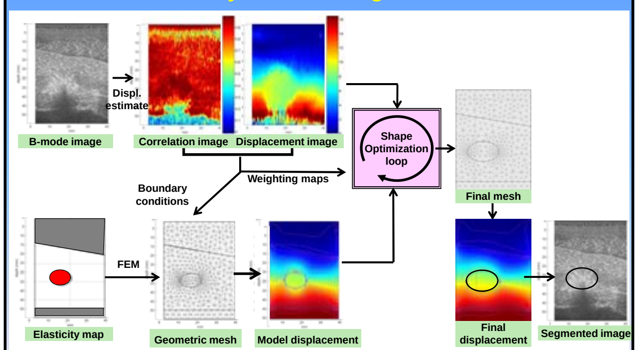
Elasticity-based Segmentation



$$\rho \frac{\partial^2 u}{\partial t^2} - \nabla \bullet c \nabla u = K$$

Navier's equation

Elasticity-based Segmentation



$$\hat{S} = \arg\min\{\Im(S) = \sum_{i=1}^{N}\sum_{j=1}^{M} W(i,j)\left\|\hat{u}(i,j) - u(i,j;S)\right\|^{L1}\}$$

Moving from ex vivo to in vivo

- Real-time strain imaging or rapid interactive rate
- Robustness to uncontrolled motion
- High resolution, SNR and CNR
- 2D (or 3D) extension
- High axial compression
- Insensitivity to signal decorrelation

Dynamic programming approach

Amplitude similarity

$$\Delta(i,d) = |g(i) - g'(i+d)|$$

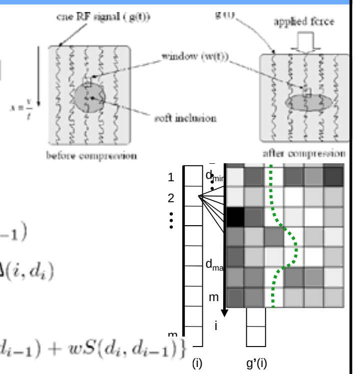
Smoothness

$$S(d_i, d_{i-1}) = (d_i - d_{i-1})^k$$

Recursive cost function

$$C(i,d_i) = \min_{d_{i-1}} \{C(i-1,d_{i-1}) + wS(d_i,d_{i-1})\} + \Delta(i,d_i)$$

$$M(i,d_i) = \arg\min_{d_{i-1}} \{C(i-1,d_{i-1}) + wS(d_i,d_{i-1})\}$$



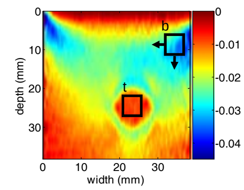
• Hager et al., PAMI 2003; Hall et al., US IEEE Sym. 2006;

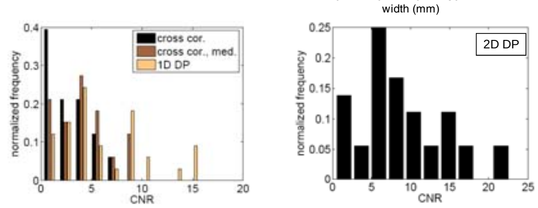
Contrast to Noise Ratio

$$\mathrm{CNR} = \frac{C}{N} = \sqrt{\frac{2(\bar{s}_b - \bar{s}_t)^2}{\sigma_b^2 + \sigma_t^2}}$$

• Target window is fixed on the lesion

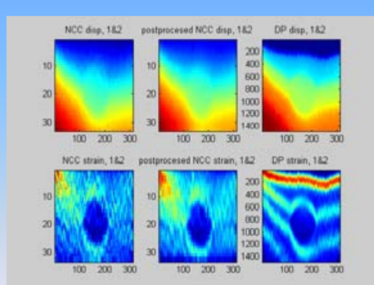
• Background window, is moved across the strain image



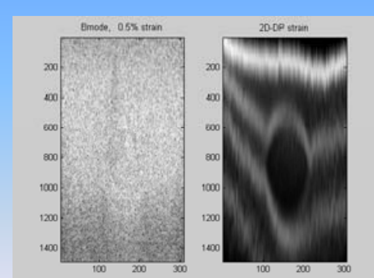


• Rivaz et al., TMI 2008.

Dynamic Programming Elastography vs. Normalized Cross-correlation Methods

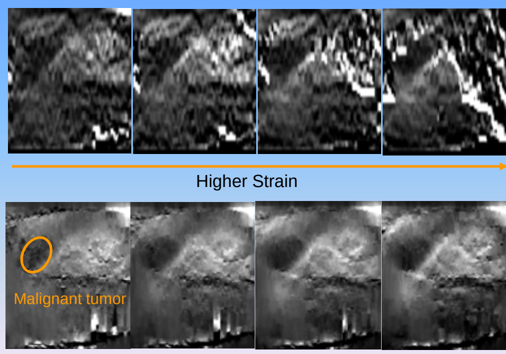


2D Dynamic Programming Elastography



Freehand Palpation of Resected Prostate

NCC



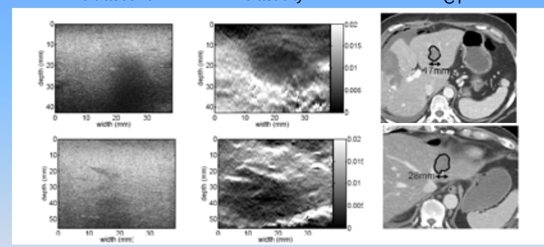
DP

In vivo Patient Studies

ultrasound | elasticity | post-operation CT

patient 1

patient 2



thermal lesion not visible

thermal lesion visible!!

Rivaz et al., MICCAI 2008

Challenges and Possible Solutions

- From 2D to 3D displacement
- Effective and rapid visualization
- ***Optimal*** real-time elasticity imaging
- Large animal model for in vivo validation

3D Elasticity Imaging of Ablation

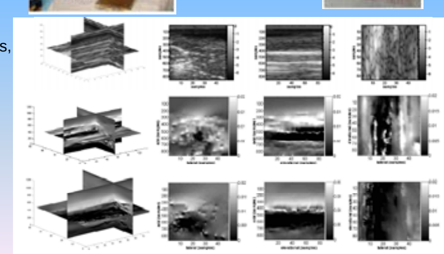
experimental setup

pathology

ultrasound images, After 10 min

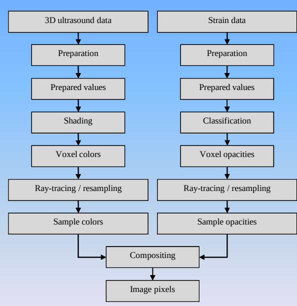
elasticity images, After 6 min

elasticity images, After 10 min



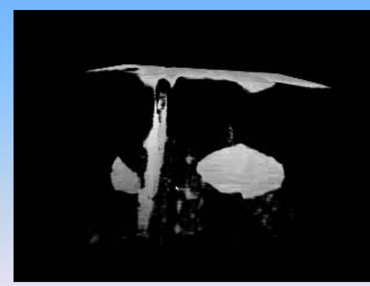
Rivaz et al., MICCAI 2008

Elasticity-based Volume Rendering of 3DUS B-mode data



Ray Casting Volume Rendering Pipeline Based on Strain Data as Opacity Volume

Elasticity-based Volume Rendering of 3DUS B-mode data



Acknowledgements

Research Collaborators:
Gregory Hager (Research Director)
Russell Taylor (Director)
Iulian Iordachita (CS, Hopkins)
Gabor Fichtinger (CS, Queens)
Roger Ghanem (CE,USC)
Gregory Chirikjian (ME, Hopkins)
Jin Kang (ECE, Hopkins)
Jim Spicer (ME, Hopkins)
Colleagues and Staff in the ERC and LCSR

Funding:
• SIEMENS Corporate Research, pre-doctoral fellowship
• NSF EEC 9731478, ERC Center Grant
• BCRF

Clinical Collaborators:
• Michael Choti, M. Awad, L. Assumcao, M.DeOliviera (Surgery, Hopkins)
•Ted DeWeese, Danny Song, R. Zellars (Rad-On, Hopkins)
• Ron Kikinis (Surgical Planning Lab, BWH)

Industrial Collaborators:
• Frank Sauer, Ali Khamene, Wolfgang Wein (SIEMENS Corporate Research)
• Shelby Brunke, SIEMENS Ultrasound Dept.
• CMS, Burdette Medical Systems
• Intuitive Surgical Inc.
• Aloka Ultrasound

MUSiiC Research Laboratory | Laboratory for Computational Sensing + Robotics | ERC | CISST | JOHNS HOPKINS UNIVERSITY

Thank you !

Follow-up:
Emad Boctor
eboctor@jhmi.edu

MUSiiC Research Laboratory | Laboratory for Computational Sensing + Robotics | ERC | CISST | JOHNS HOPKINS UNIVERSITY